

# **R&D activities for the sustained spheromak approach to magnetic fusion energy**

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Fusion Power Associates 41<sup>st</sup> Annual Meeting  
December 16 – 17, 2020

# Outline

- Sustained spheromak overview
- Summary of motivating results
- Ongoing R&D activities
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# Spheromaks are compact, toroidal magnetized plasmas in the compact torus (CT) family

- Spheromaks are compact, toroidal magnetized plasmas contained in a simply-connected confinement volume
- Spheromaks have both toroidal ( $B_T$ ) and poloidal ( $B_p$ ) magnetic fields generated by plasma current, with no externally applied  $B_T$
- Safety factor  $1 > q > 0$ , which is generally higher than a reversed-field pinch (RFP) ( $q < 0$  in edge) but lower than in a tokamak ( $q > 1$ )
- Large plasma currents require efficient sustainment while maintaining good energy confinement for a favorable scaling towards fusion conditions

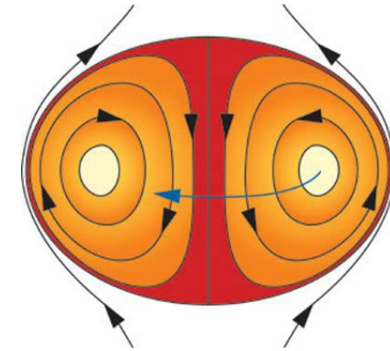
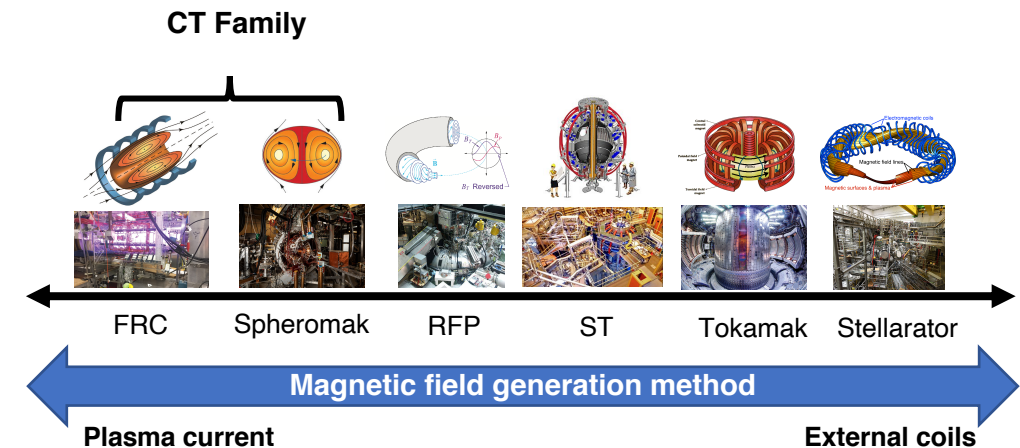
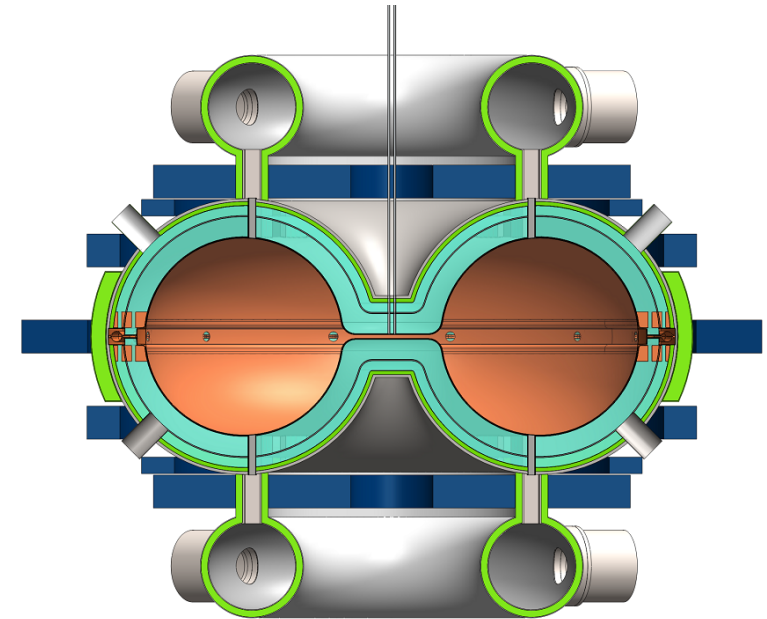


Figure: UW A&A Department,  
<https://www.aa.washington.edu/research/HITsi/research/spheromak>



# Potential benefits of sustained spheromak magnetic fusion reactors motivate continued R&D

- Large plasma current allows for possibility of Ohmic ignition if confinement is sufficiently good, eliminating the need for auxiliary heating systems
- Elimination of toroidal field coils (TFCs) and central solenoid (CS) reduces usage of superconducting coils
- Removal of TFCs and CS allows for improved utilization of inboard fusion neutrons for generating tritium with thick, liquid immersion blankets
- One superconducting equilibrium coil set is required for continuous operation, which can be well protected from fast neutrons for long lifetimes
- Features provide for the possibility of a compact, high power density, simpler fusion power core, assuming successful scaling to reactor-relevant plasma parameters [1]



[1] “Dynamak” 1 GWe reactor vision based on sustained spheromak

[1] D.A. Sutherland, et al., *Fus. Eng. and Des.* **89**, 4 (2014), <https://doi.org/10.1016/j.fusengdes.2014.03.072>.

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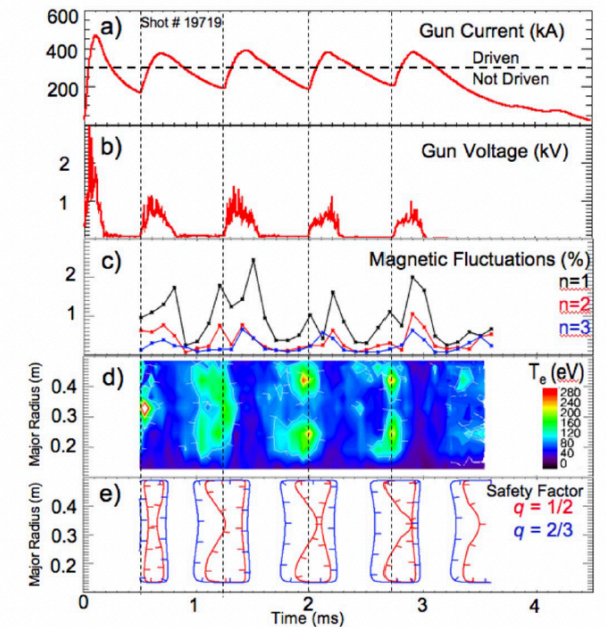
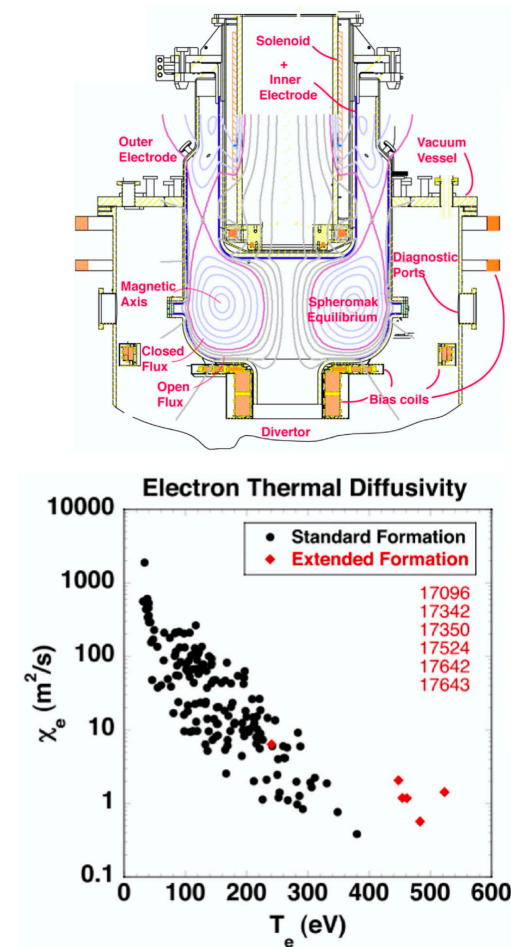
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# Best performance to date was seen in the SSPX experiment at LLNL during extended formation discharges [2]

- SSPX used coaxial magnetic helicity injection (CHI) to form and sustain spheromak configurations in a cylindrical flux conserver

$$\dot{K} = 2 \int_v \vec{E} \cdot \vec{B} dV = 2V_{inj}\psi_{inj}$$

- During extended formation discharges, electron temperatures  $T_e > 0.5$  keV and thermal diffusivity  $\chi_e$  approaching L-mode of a tokamak were observed [2]
- However, during sustainment phases, a degradation of confinement quality was observed due to excitation of plasma instabilities
- Additionally, low current gain  $G = I_{tor}/I_{inj} \sim 2$  would lead to unattractive scaling towards reactor conditions with very large  $I_{inj}$  flowing through electrodes



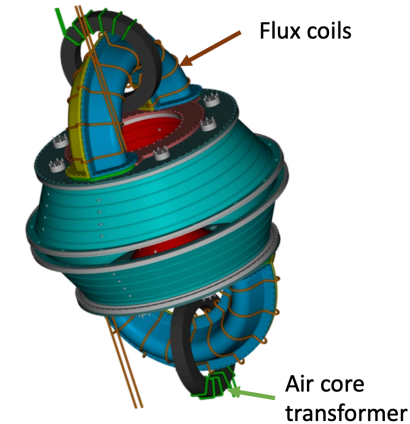
[2] B. Hudson, et al., *Phys. Plasmas* **15**, 056112 (2008), <https://doi.org/10.1063/1.2890121>.

# Spheromaks sustained with steady, inductive helicity injection (SIHI) aim to overcome these challenges with key technical differences

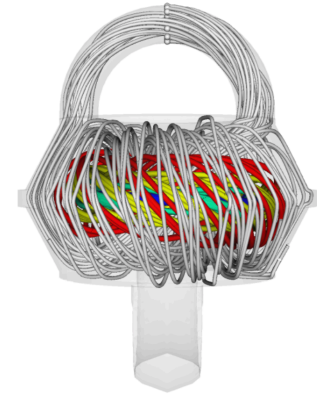
- Steady, Inductive Helicity Injection (SIHI) is used on the HIT family of experiments to form and sustain spheromak configurations
- SIHI imposes non-axisymmetric perturbations needed for dynamo current drive on spheromak equilibria while injecting magnetic energy and helicity
- Eliminates need for electrodes with fully inductive operation, providing more attractive engineering requirements than a CHI-driven spheromak system
- Helicity injectors operate AC in kHz range, but temporal phasing with multiple injectors allows for the continuous injection of magnetic helicity
- The current HIT-SI3 experiment has two injector phasings (60° and 120°) that provides steady, inductive helicity injection with varying imposed magnetic perturbation spectra

## Previous HIT-SI Experiment

HIT-SI coils and geometry

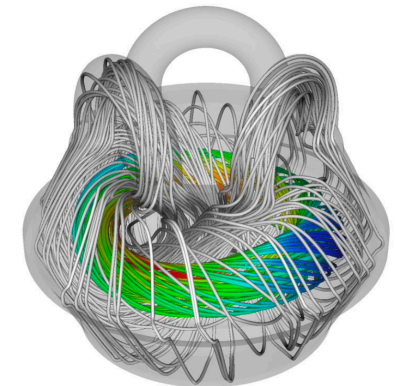
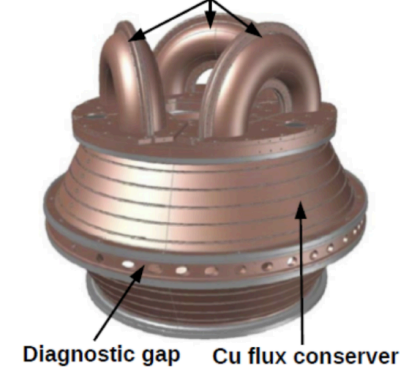


Taylor state equilibrium  
 $\nabla \times \vec{B} = \lambda \vec{B}$ , where  $\lambda \equiv \mu_0 \vec{j} / \vec{B}$



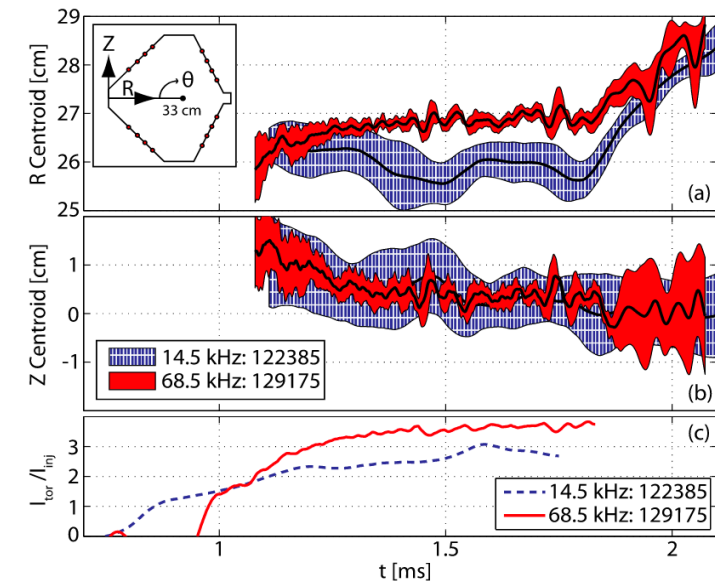
## Current HIT-SI3 Experiment

Inductive helicity injectors



## Record current gains for sustained spheromaks were produced in the HIT-SI experiment while operating at $f_{inj} \sim 68.5$ kHz

- Sustained spheromaks have reached a current gain  $G = I_{tor}/I_{inj} \sim 4$  in the HIT-SI experiment operating at  $f_{inj} \sim 68.5$  kHz [5]
- Reaching high current gain is a key requirement for the viability of the sustained spheromak approach to magnetic fusion energy – reactors will require  $G \sim 10^2 - 10^3$
- Extended-MHD (xMHD) simulations with both the NIMROD and PSI-Tet codes indicate higher current gains may result from higher plasma temperatures [6], larger plasma size [6], and lower plasma density [7]
- The combined usage of experimental data, xMHD simulations and equilibrium models will inform a self-consistent startup and operating point of a high current gain, SIHI-driven spheromak configuration



[5] Current centroid positions and current gain  $G = I_{tor}/I_{inj}$  vs. time at low and high injector frequencies.

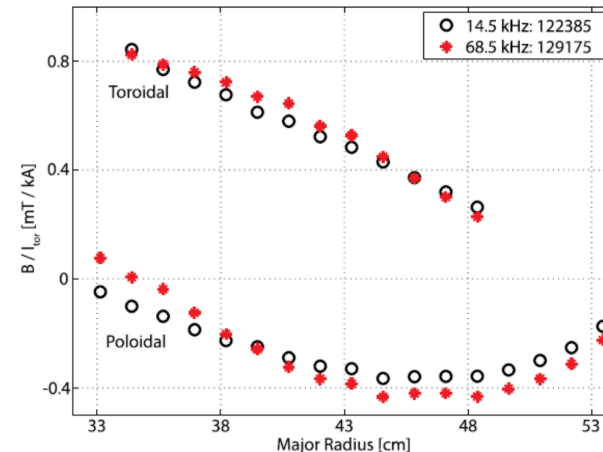
[5] B.S. Victor, et al., *Phys. Plasmas* **21**, 082504 (2014), <https://doi.org/10.1063/1.4892261>

[6] Kyle Morgan, et al., *Nuc. Fus.* **59**(6), 066037 (2019), <https://doi.org/10.1088/1741-4326/ab1779>

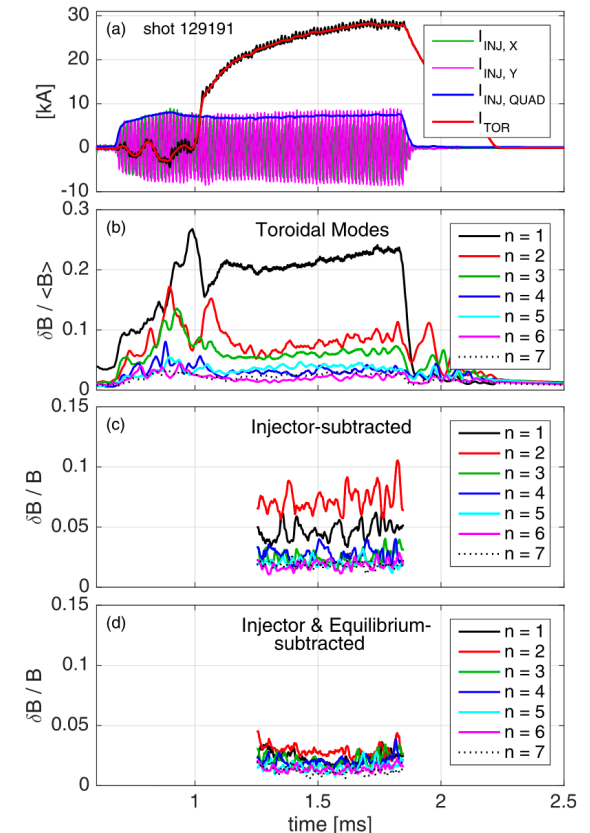
[7] A.A. Kaptanoglu, et al., *Phys. Plasmas* **27**, 072505 (2020), <https://doi.org/10.1063/5.0006311>

# Experimental evidence suggests stable sustainment with pressure confinement with SIHI with majority of non-axisymmetric magnetic fields imposed by injectors

- A Shafranov shift is observed in HIT-SI while operating at high injector frequency – potential evidence of plasma pressure confinement
- Bi-orthogonal decomposition indicates that majority of non-axisymmetric magnetic activity is imposed by injectors rather than being instability driven
- After subtracting equilibrium and injector correlated non-axisymmetric fields, low levels of non-axisymmetric activity suggests stability to low-order instabilities during sustainment
- These results are promising, though plasma temperature  $T_i + T_e < 100$  eV – stable sustainment must be demonstrated in higher temperature plasmas



[5] B.S. Victor, et al., *Phys. Plasmas* **21**, 082504 (2014), <https://doi.org/10.1063/1.4892261>



[3] A.C. Hossack, et al., *Phys. Plasmas* **24**, 020702 (2017), <https://doi.org/10.1063/1.4975663>

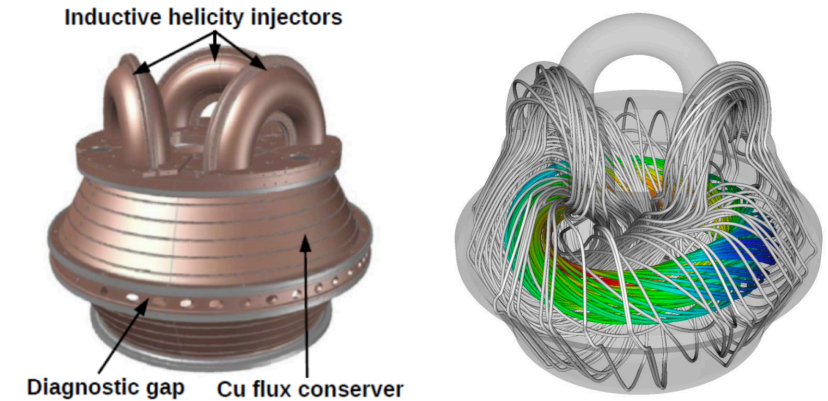
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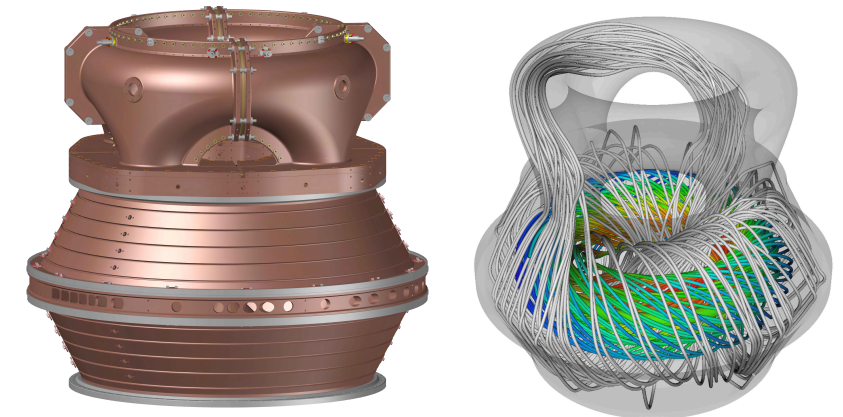
## Ongoing R&D includes the installation of a new SIHI system and power upgrades to increase sustained spheromak plasma performance

- **To access higher performance SIHI-driven spheromak regimes:**
  - Increase SIHI power injection and energy storage for high power, longer duration shots ( $P_{inj} > 20$  MW for  $\sim 3$ -5 ms)
  - Build and install a new, helicity injection manifold to facilitate low density breakdown and improved magnetic perturbation control
  - Install a helicon pre-ionization system in HIT-SIU manifold to aid in low-density breakdown and pre-ionized fueling
- High-power HIT-SI3 operations are underway, and HIT-SIU operations will begin in early-2021
- Supporting theoretical and computational R&D with experimental results to finalize following Proof-Of-Concept (POC) design point
- Primary experimental goal is to demonstrate SIHI-driven spheromaks with  $T_e, T_i > 100$  eV using SIHI
- These stages of our concept exploration (CE) phase of R&D are being funded by ARPA-E through OPEN 2018 and BETHE programs

HIT-SI3 Experiment (2015-2021)

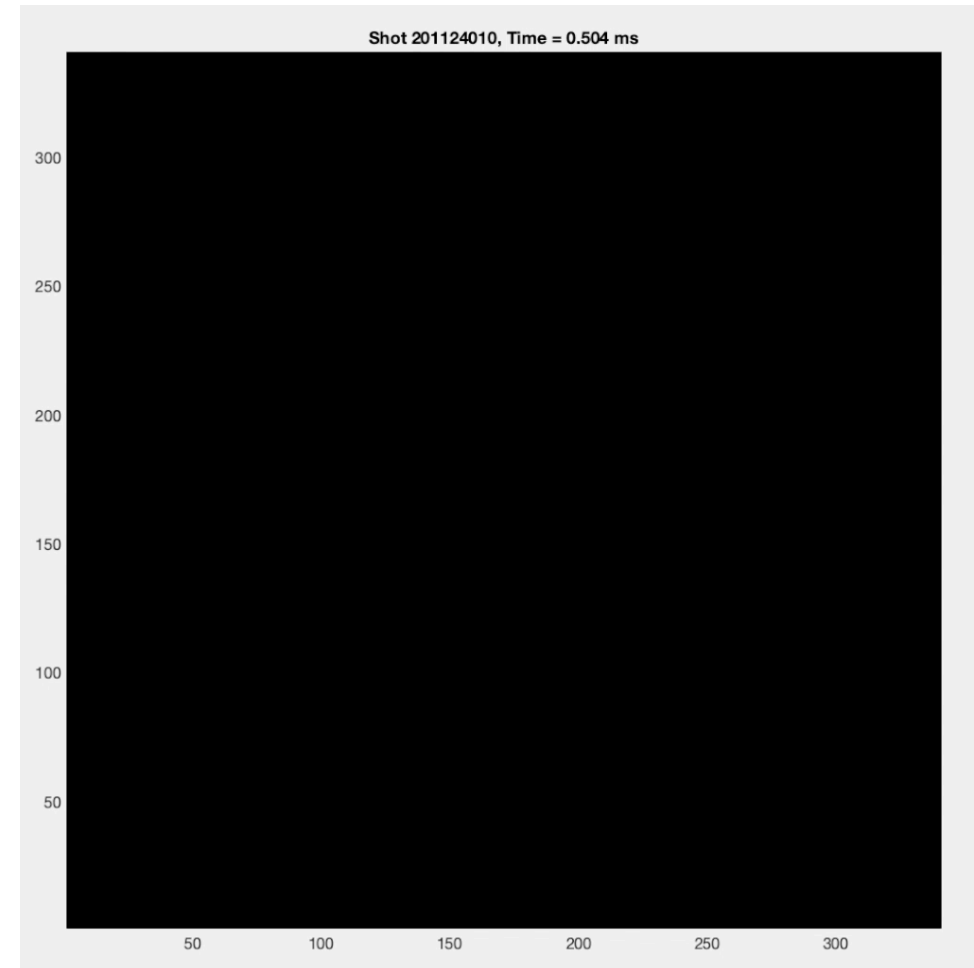


HIT-SIU Experiment (2021)



## High-power HIT-SI3 operations currently underway

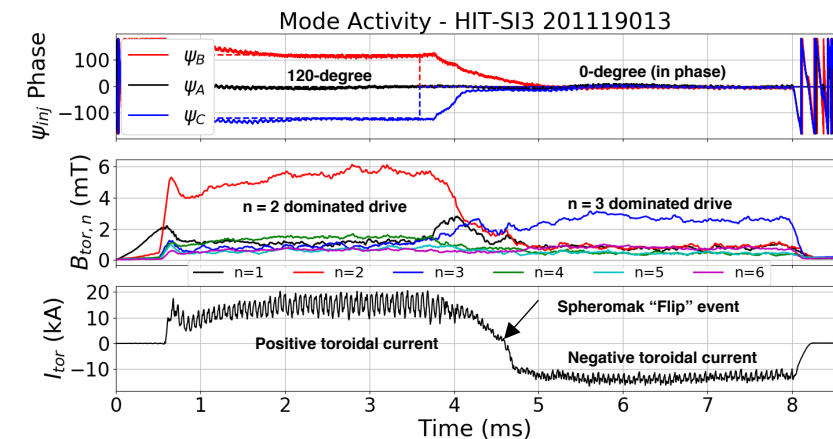
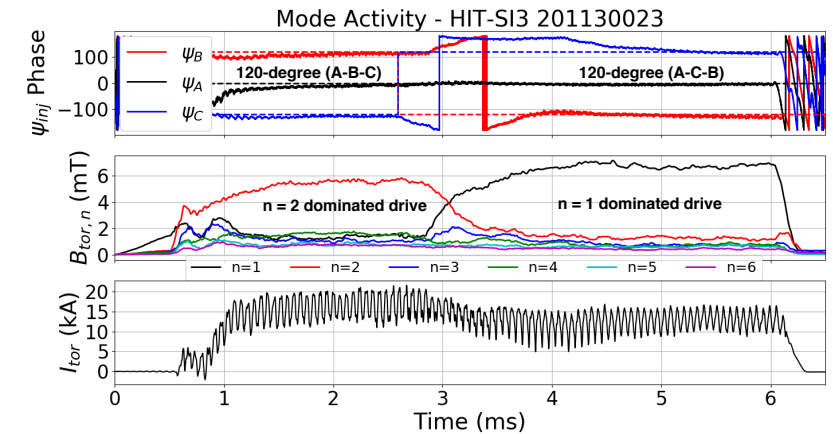
- High speed camera imaging of two SIHI injector mouths during a shot
- Injectors operate at 16.6 kHz while continuously injecting magnetic helicity and energy
- Gas puff valves fuel helicity injectors with He and/or D<sub>2</sub> gas
- After the high-power HIT-SI3 campaign, the three injectors will be replaced with a new helicity injection manifold on HIT-SIU



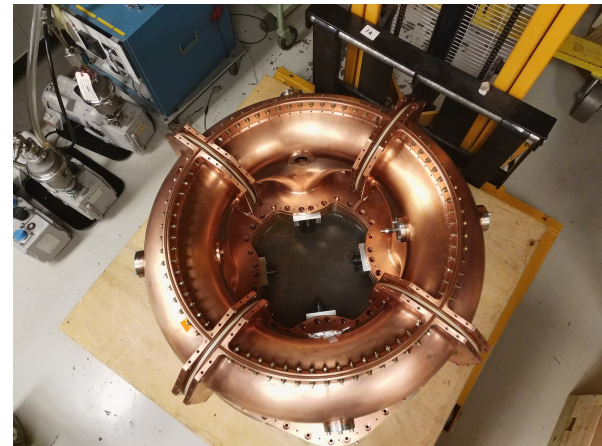
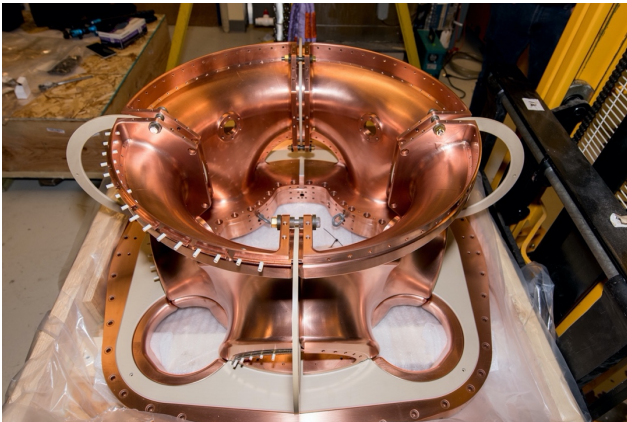
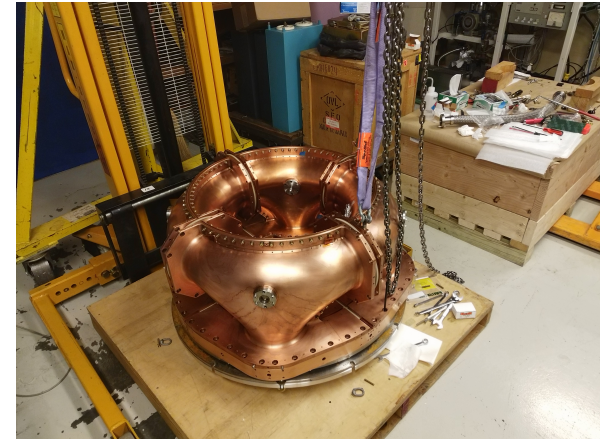
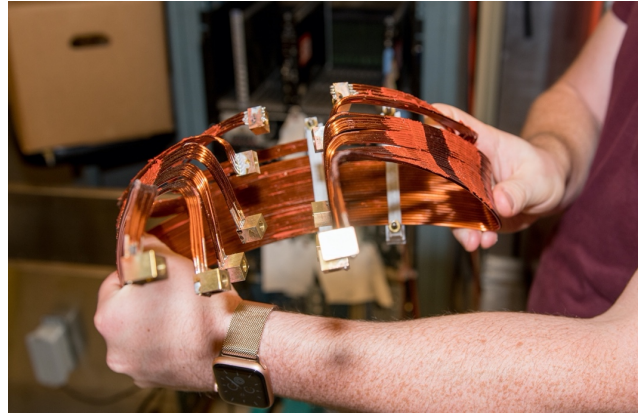
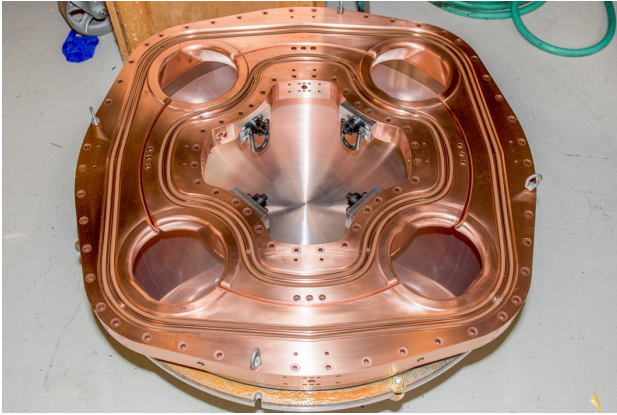
## A new GPU-based feedback control system provides improved control of imposed non-axisymmetric magnetic perturbations for dynamo current drive\*

- Changing the temporal phasing of the three helicity injectors on HIT-SI3 provides for different imposed magnetic perturbation spectra
- Injector phasing can now be changed during a shot to change perturbation spectrum while sustaining spheromaks
- Injector phasing optimization is currently underway to maximize sustained spheromak performance
- Feedback control system will also be used on HIT-SIU helicity injection manifold once operations begin in mid-2021

\*Developed by K.D. Morgan (CTFusion & University of Washington)



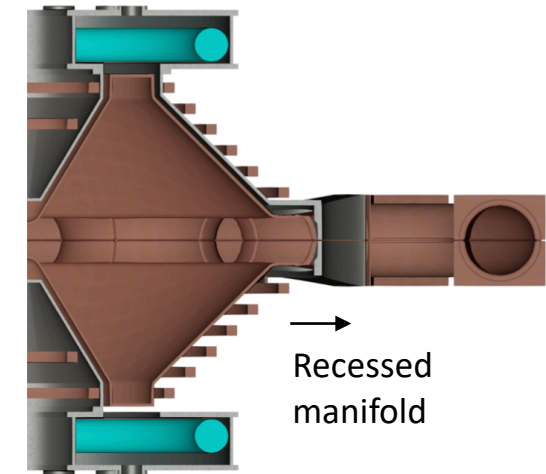
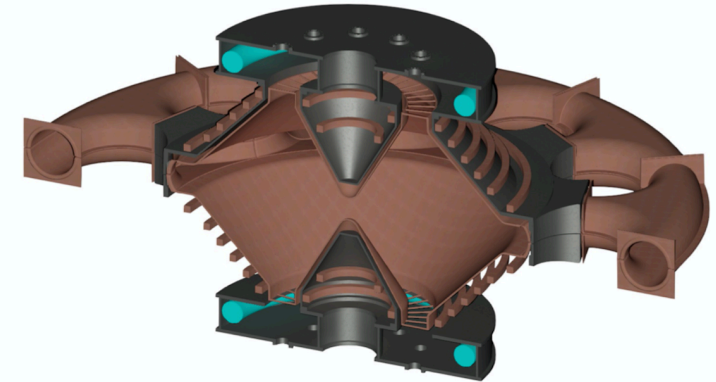
# HIT-SIU helicity injection manifold has been manufactured and assembly is underway



## Following the completion of the concept exploration (CE) phase of R&D, a Proof-Of-Concept (POC) device aims to demonstrate $T_i, T_e \geq 1$ keV during sustainment

- The next Proof-Of-Concept (POC) device is being designed with the primary goal of demonstrating sustained spheromaks with  $T_i, T_e \geq 1$  keV using SIHI
- Significant size increase to  $R_o = 0.75$  m,  $a = 0.50$  m (2.3x linear size of HIT-SIU)
- An outboard, midplane SIHI system will provide  $n = 1 - 5$  modal control of imposed magnetic perturbations in a more reactor-compatible geometry
- A Cu equilibrium coil set is used to extend pulse duration to 100s ms needed to Ohmically heat to  $T_i, T_e \geq 1$  keV
- Avoids low-q rational surfaces in the edge to help mitigate tearing activity, and helicity injection manifold is recessed to prevent the generation of magnetic islands resonant with non-axisymmetric machine features
- POC will confirm scaling laws towards higher performance devices to follow

### Proof-Of-Concept (2021-2025)



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- Spheromaks may provide a path toward fusion that results in a compact, simple, and cost-effective fusion reactors, if successfully scaled to fusion plasma parameters
- SIHI is being used to form and sustain spheromaks on the HIT family of experiments to overcome past limitations of CHI – evidence of stable sustainment with pressure confinement is promising, though must be demonstrated with higher plasma temperatures
- Power upgrades and a new helicity injection manifold system on HIT-SIU currently underway to increase sustained spheromak performance to a level consistent with the end of concept exploration (CE) phase of R&D during 2021
- Aim to build and operate a new proof-of-concept (POC) device to pursue sustained spheromak operations with  $T_i, T_e > 1$  keV following completion of ARPA-E funded concept exploration (CE)